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PHYSIOGRAPHIC RELATIONS OF SERPENTINE, WITH SPECIAL REFERENCE TO THE SERPENTINE STOCK OF STATEN ISLAND, N.Y.

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The serpentine highland of Staten Island is one of the most anomalous physiographic features of the Cretaceous peneplain of the Atlantic seaboard. This ancient and widespread base-level slopes southeastward and seaward from the highlands of Southern New York and Northern New Jersey; and from the latter district it has been designated, locally, the Schooley Plain. In its approach to the coast it is most continuously and perfectly preserved in the long, straight crest of the Palisade trap ridge. This approach is, in fact, unbroken to Kill Van Kull; and the peneplain passes below sea-level in the northwestern quarter of Staten Island. The normal seaward gradient of the peneplain, in the vicinity of the coast, as proved by numerous deep borings, ranges from 75 to 100 feet per mile; and nowhere else is it so perfect and so perfectly preserved as where it is still covered and protected by the Cretaceous sediments beneath which it was progressively buried as it slowly sank below sea-level, and in so sinking received its finishing touches in the addition of marine planation to terrestrial peneplanation.

Beneath the southeastern and southern plain or lowland of Staten Island, the peneplain, developed here on the Manhattan schists, has been found by the drill at depths (increasing seaward) of 200 to 400 feet, or just where its normal gradient would have led us to expect it. But between the northwestern and southeastern lowlands the continuity of the buried peneplain is interrupted by the great lenticular stock of serpentine nearly eight miles long from northeast to southwest and fully three miles in maximum breadth, and rising to an extreme height of nearly 400 feet above the sea, or 400 to fully 800 feet above the encircling peneplain. The southeastern slope, especially, of this relief is very abrupt and in part almost precipitous, the boldness of the ridge being, in general, one of its most impressive aspects. It is noteworthy, also, that it consists entirely of serpentine and embraces the entire known area of the serpentine. The Manhattan schist on the southeast side of the ridge and the Triassic trap and sandstone on the northwest side, are wholly outside of the highland area, being strictly confined to the lowland or, rather, to the underlying peneplain, although the trap, at least is far more resistant than the serpentine.

The serpentine relief clearly holds the general or formal relation of a monadnock to the Cretaceous peneplain above which it towers; and this most obvious interpretation of the Staten Island bedrock relief demands the first consideration. In this connection it may be noted that serpentine, owing to its insolubility and general chemical stability, imperviousness, massive structure, and tight joints offers greater resistance to erosion than its inferior hardness would indicate; and it is not improbable that in the relatively inert nature of the stone we have an adequate explanation of some of its topographic reliefs, especially where the surrounding formations are of a weak and yielding character. A general survey of serpentine occurrences, the world over, shows, however, that, almost regardless of the geologic environment, they are, if of a massive character (stocks, dikes, etc.), characterized by topographic relief.

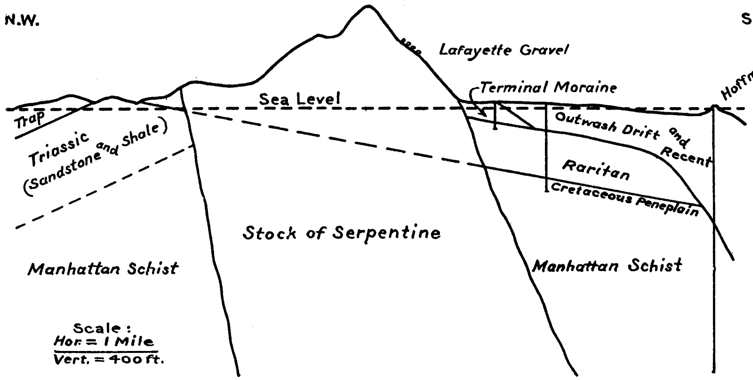

FIG. 1.—Cross-section of Staten Island, showing the geologic and topographic relations of the stock of serpentine.

Evidently, some other factor than differential erosion is required for a full and satisfactory explanation, especially in the case of such an ancient and pronounced serpentine relief as the Staten Island highland, standing, as it does, in close proximity to the coast and to the mouth of a large river. It is simply inconceivable that with its more complete exposure to the agents of erosion—subaerial, fluvial, and marine—the Staten Island serpentine stock should have been able successfully to resist erosion and maintain its high relief throughout the period during which the far harder and more resistant diabase of the nearby Palisade ridge was completely base-leveled.

The obvious inadequacy of the monadnock or residuary-relief explanation of the serpentine heights of Staten Island has led Willis and Dodge[1] to explain the relief of the serpentine by faulting. According to this explanation, Staten Island Heights would seem to stand as a solitary instance on our entire Atlantic seaboard of important post-Cretaceous faulting not due to glacial agency; and glacial drag and thrust must be powerless to elevate the bedrock *en masse*, especially at the extreme limit of the ice invasion. It is, however, further suggested by Willis and Dodge that this supposed faulting may be correlated with that traversing the Newark (Triassic) rocks of New Jersey; although it is commonly conceived that the faults of the Triassic strata date from Triassic time. Were they post-Cretaceous, they could not fail to break the continuity of the Cretaceous peneplain elsewhere than on Staten Island. The suggested faults would be rather unique, also, in closely circumscribing the serpentine area without traversing or breaking the inclosing schist or the Triassic sandstone and trap. Evidently, this explanation is not altogether satisfactory; and it appears advisable to seek further. In fact, we seem forced to the conclusion that the serpentine possesses an inherent power of growth or self-assertion that has enabled it, progressively, to lift its head above the base-level to which it may have been at least approximately reduced in Cretaceous time.

Assuming, as we must, that this great stock of massive and essentially structureless serpentine has been derived from some massive, basic, and highly magnesian igneous rock, such as peri-

[1] *U.S. Geol. Survey, Folio 83; Science*, February 20, 1903.

dotite, we find in the process of serpentinization and the consequent inevitable expansion the requisite innate power of growth and topographic rejuvenation. This alteration, of which hydration is now the most important phase, and which is simplest, most direct, and most important for the mineral olivine, involves in every case a notable diminution of density and increase of volume, the volumetric gain, according to Van Hise,[1] ranging, with different species and varying conditions, approximately from 15 to 40 per cent. It is, of course, to this notable expansion that we owe the tightness of the joints and the internal slickensides and slip-fiber veins so characteristic of massive serpentine.

Under the conditions surrounding an approximately vertical plug or stock, at a great depth in the earth, the expansion due to serpentinization cannot be, to any large extent, isometric (cubic), but must take place chiefly or wholly upward, that is, in the direction to give it the maximum topographic value. This means that for the maximum ratio of expansion, 40 per cent, and ignoring contemporaneous erosion, the surface exposure of the serpentine stock would be elevated nearly 40 feet for every 100 feet in depth of peridotite altered to serpentine; or one-half as much for an assumed mean expansion of 20 per cent. These relief or topographic values may, however, be exceeded in the cases, probably numerous, where the diameter of the stock increases downward, the sepentine then reaching the surface by accelerated flow through a more or less contracted vent.

If we assume, with Van Hise,[2] that serpentinization is limited to the zone of katamorphism, the estimated depths of which range from 30,000 to 40,000 feet, the total vertical expansion in this zone, even for the minimum ratio, would still account many times over for the relief of the pseudo-monadnock of Staten Island Heights—a monadnock developed, in the main at least, subsequently to the peneplanation and in a manner suggesting comparison, rather, with the growth of the spine of Mont Pelé.

We have here, apparently, a new physiographic type, a variety of auto-relief not heretofore clearly recognized; and comparison with the spine or obelisk (pelélith) of Mont Pelé is inevitable The pelélith, we may suppose, resulted from the extrusion (or protrusion)

[1] *U.S. Geol. Survey, Monograph 47.* [2] *Ibid.*

of a solid, and in the lower part merely a highly viscous, plug of lava by the vertical expansion of less viscous lava beneath, through the separation, due to cooling and relief of pressure, of aqueous and other vapors and various gases. The serpentine relief of Staten Island, on the other hand, is believed to be due to the extrusion (or protrusion) of a plug or stock of serpentine by the vertical expansion resulting from the progressive downward growth of the serpentine through the hydration and consequent swelling of the anhydrous magnesian rock in the alteration of which it has its origin. Reliefs formed after the manner of the Mont Pelé obelisk are now known as *pelēliths;* and parity of usage suggests *statenliths* as an appropriate designation for serpentine reliefs formed on the plan or after the manner of Staten Island Heights. It is, of course, conceivable that a rock formation, antecedent or subsequent, covering a serpentine stock may, by continued upward growth of the latter, be lifted into a dome; and such a dome, somewhat comparable with a laccolithic dome, may be called a statenlithic dome.

For proof that the statenlith of Staten Island is not unique, a solitary instance, we need look no farther than Castle Point, in Hoboken, between 7 and 8 miles north of Staten Island and approximately on the line of strike of the Staten Island serpentine stock. This point forms a hill about half a mile long and 100 feet high, consisting exclusively of serpentine. It holds the formal relation of a monadnock, not to the Cretaceous peneplain, but to the topographically lower Miocene base-level or partial peneplain very perfectly developed on the Manhattan schist and Triassic sandstone and shale of Hoboken and Jersey City. That this relatively small serpentine relief, standing on the very brink of the deep, buried gorge of the Hudson, post-dates the base-leveling of the inclosing formations is most probable. It is, thus, essentially similar in its geologic and physiographic relations to the Staten Island serpentine, a parallel instance, and unquestionably a true statenlith.

The question naturally arises at this point as to whether or not statenliths include only serpentine reliefs; and the answer must be that, on theoretic grounds, at least, various other secondary, hydrous silicates are entitled to recognition, notably the chlorites and probably talc. The chlorites are chiefly derived from augite, hornblende, and biotite; and the total expansion, including accessory epidote, quartz, iron oxide, etc., ranges approximately, according to Van Hise,[1] from 10 to 25 per cent. We are not restricted here to bodies of pure or approximately pure chlorite, such as chlorite schist; but may properly take account, also, of the vastly more extensive chloritic rocks known collectively as greenstones —massive, basic, igneous rocks (diabase, diorite, gabbro, etc.)— which have, in the zone of katamorphism, undergone the greenstone alteration, of which chloritization is the principal phase. The outcrops of dikes, stocks, etc., of greenstone are commonly protuberant; and if more salient than the relatively resistant nature of the rock would lead us to expect, we may find in the expansion, of which the chloritization is a reliable index, an entirely adequate explanation. Furthermore, the differential movement resulting from the expansion is very generally attested by internal slickensides.

Again, if the question be raised as to whether statenliths are necessarily limited to silicate rocks, the answer, on theoretic grounds at least, must be in the negative; for the hydration of anhydrite to form gypsum involves, in the absence of solution, the very notable expansion of 60.3 per cent; and the resultant deformation, it is well known, may be very severe. Also, it is matter of common knowledge that gypsum, in spite of its extreme softness and ready solubility, is not infrequently characterized by decided relief, and may be classed as to some extent a hill-forming rock. Occurring mainly or normally as a sedimentary deposit, it must, however, lack the power of persistent topographic rejuvenation, save where the strata have exceptional thickness or are highly inclined.

The dynamic and structural relations of the statenliths to the various other types of relief are expressed in the following systematic outline:

OUTLINE OF A GENETIC CLASSIFICATION OF RELIEFS

Superficial Agencies
  Destruction (erosion) reliefs
    Youth = continuous, lobate plateaus
    Maturity = connected, dendritic ridges
    Senility = isolated hills—monadnocks

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[1] *U.S. Geol. Survey, Monograph 47.*

- Construction (accretion) reliefs
    - Littoral and fluvial = spits, bars, deltas
    - Eolian = dunes
    - Glacial = drumlins, moraines, eskers, kames

Subterranean Agencies

- Construction (accretion) reliefs
    - Igneous extrusion = volcanoes and pelêliths
    - Igneous intrusion = laccoliths and laccolithic domes
    - Aqueous extrusion = tufa cones and terraces
    - Aqueous intrusion = crystosphenes and saline domes[1]
- Deformation reliefs
    - Plication = anticlinal and monoclinal ridges, domes and plateaus
    - Dislocation = block mountains and plateaus
    - Hydration and vertical swelling = statenliths and statenlithic domes

Serpentine is a rock of rather restricted distribution. In Eastern North America it is chiefly confined to the narrow and discontinuous Appalachian belt of peridotite and other basic magnesian rocks (to the alteration of which the serpentine owes its origin) in the western margin of the seaboard zone of crystalline rocks (igneous and metamorphic). In this belt, extending from Newfoundland and Gaspé Peninsula to Central Alabama, the basic magnesian rocks tend to occur in a series of isolated lenses (lenticular stocks and dikes) the axes of which coincide with the strike of the enclosing gneiss and schist.[2] The Staten Island and Hoboken stocks of serpentine are thus seen to be entirely typical in their structural relations; and it is a legitimate inference from these that all of the stocks in which serpentinization is well advanced are, theoretically at least, statenliths. Many of the serpentine stocks exhibit actual relief, notwithstanding the resistant nature of the inclosing formations; but rarely, probably, is the relief so marked or so sharply defined as in the type example.

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[1] A crystosphene, as defined by Tyrell (*Journal of Geology*, XII, 232–36), is a lens of ice formed in or beneath the tundra of high latitudes and arching up or doming the overlying materials. It is here proposed to broaden the definition to include the saline domes of the Gulf Coastal Plain and, in general, all instances where the surface has been domed by mineral (ice, salt, sulphur, gypsum, etc.) segregation and crystallization. This appears permissible, since crystosphene may equally well be translated ice-wedge or crystal-wedge.

[2] *North Carolina Geological Survey*, Vol. I, Plate 4.

In Central Alabama the basic magnesian and serpentine belt passes beneath the Coastal Plain and the conditions become favorable to the occurrence of statenlithic domes. It is interesting, therefore, to find directly on this line 90 miles and 120 miles respectively, from the border, the Lower Peach Tree anticline and the Hatchetigbee anticline, the one intersected by the Alabama River and the other by the Tombigbee River. These deformations of the Coastal Plain sediments are essentially unique east of the Mississippi. That they are normal folds, due to horizontal compressive stress, is sufficiently improbable to suggest that they may be either saline domes or statenlithic domes; and it is hoped that the testimony of the drill will decide the matter in the near future.

Although these anticlines have marked geologic relief, the upward arching of the Eocene, and, presumably, of the Cretaceous strata amounting to hundreds of feet, they are devoid of topographic relief, the Pliocene (Lafayette) strata crossing them without deviation. In other words, they were base-leveled in Pliocene time and have suffered no subsequent deformation, the power of growth, whatever its source, seeming to be quiescent or exhausted. A further distinct indication that they are not true statenlithic domes is found in the fact that their axes, trending with the strike of the Coastal Plain formations, are directly transverse to the course of the basic magnesian or serpentine belt.

It appears, then, that an unquestionable statenlithic dome remains to be identified; although it may be suggested in passing that in so far as the saline domes are due to the derivation *in situ* of gypsum from anhydrite they belong to this new type of relief.

The contact of the statenlith with the bordering formations is a true fault; and to this extent Willis and Dodge are right in their interpretation of Staten Island geology. But they err, as I believe, in correlating the obvious displacement with ordinary fracture and slip faults and with the extended, rectilinear displacements of the Triassic strata. The latter originated in a profound crustal readjustment involving the entire depth of the katamorphic zone and tapping, in some cases, reservoirs of the most truly abyssal magmas. The statenlith displacement, on the other hand, strictly limited to the periphery of the serpentine stock and to the katamorphic zone, finds its origin in the quiet and unobtrusive chemical reactions of that zone involved in the secular absorption and downward penetration of meteoric water, and the displacement must, obviously, die out downward.

Apparently, then, we have in the statenlith not only a new physiographic type, but also, in its periphery, a hitherto unrecognized type of fault, a type finding its origin in the localized, deep-seated expansion, through hydration, of the base of the upthrow block. Assuming that the horizontal dimensions of the statenlith increase downward, the encircling fault would be, structurally at least, of the normal or gravity type.

Pursuing this subject a step further, and recognizing that reversed or thrust faults are due to horizontal compression, that normal or gravity faults are due to vertical compression, and that vertical compression can yield only normal faults, we may, on genetic grounds, distinguish two types of normal faults: first, those due to the gravitative settling of the hanging wall block; and, second, those due to the upward expansion of the footwall block. The expansion of the footwall may be, in varying proportions, both thermal and aqueous, that is, due to the absorption of heat and of water, the normal fault of this type being the precise geologic concomitant of the statenlith.

On passing now to the consideration of the relations of the Staten Island statenlith to the history of the Coastal Plain, of which it is one of the most commanding relief features, we are confronted at the outset with the question as to whether or not the statenlith's innate power of topographic rejuvenation has enabled it to keep its head above water throughout Cretaceous and Tertiary times, thus making it a perpetual watch tower guarding the mouth of the Hudson. Although continuity of relief through geologic ages, a sort of physiographic immortality, is conceivable, it is, nevertheless, highly improbable. The clearest disproof of topographic perpetuity would, of course, be afforded by overlying Coastal Plain sediments; but this evidence, unfortunately, is almost wholly wanting; although its absence proves nothing to the contrary.

The only sediment referable to the Coastal Plain series now resting upon the Staten Island serpentine is the yellow gravel

(Lafayette) scantily preserved on a bench or terrace above the steep southeast slope of the serpentine ridge, at elevations of 180 to 220 feet above the sea. Since this gravel is identical in character with the Lafayette (Beacon Hill) of New Jersey, and the elevation is that normal for the Lafayette in the latitude of Staten Island, this correlation appears inevitable; although it involves the conclusion that the elevation of the marginal part of the serpentine, relatively to the Cretaceous peneplain, has remained unchanged since Pliocene time; with the further suggestion that the central and higher part of the serpentine (180 to 360+ feet) has experienced a differential elevation of nearly 200 feet in post-Pliocene time. An alternative but not very probable view is that the serpentine was not completely base-leveled in Pliocene time. That the central part of the stock should rise most rapidly or should continue to rise after the elevation of the periphery has virtually ceased is not difficult to understand, especially if the stock becomes larger downward, since in that case serpentinization of the central part may be conceived as lagging behind the serpentinization of the peripheral part.

As the surface of the ground is lowered by erosion, the lower limit of the zone of katamorphism and of serpentinization must be correspondingly depressed; although it is probable that the latter effect tends to lag behind the former. Downward extension of serpentinization means a 15 to 40 per cent or greater upward extension of the summit of the serpentine, the topographic relief of the serpentine being, thus, constantly renewed and increased. It is probable, however, that when erosion was sufficiently long continued with reference to a definite base-level, as during the Jurassic and early Cretaceous subaerial peneplanation and marine planation of the site of Staten Island, the process of serpentinization, overtaking the slowly receding and finally stationary lower limit of the zone of katamorphism, was, for the time being, virtually exhausted. The upward growth of the serpentine then ceased; and it was, at least approximately, base levelled with the surrounding formations, and, in due course, covered by the conformable series of Upper Cretaceous and Eocene sediments.

The marked elevation and consequent extensive erosion of the land in early Miocene, substantially repeated in early Pliocene time, probably depressed the lower limit of the zone of katamorphism and thus renewed serpentinization and the topographic relief of the serpentine stock. The meager data do not permit a more detailed or definite statement; but the best general conclusion appears to be that throughout the Coastal Plain history the downward extension of serpentinization and upward extension of the serpentine stock have been active during periods of elevation and rapid erosion and quiescent during periods of base-leveling and sedimentation; and that, in spite of the present strong relief of the serpentine, developed in large part, presumably, during the great Pleistocene elevation, the successive Coastal Plain formations have been, in general, deposited across the serpentine area.

The uniformity and virtual continuity of the narrow Appalachian belt of basic magnesian stocks and possible statenliths suggests uniformity of age or practical synchronism, the indicated age being, roughly, Mid-Paleozoic, and the argument being approximately as cogent as for the Triassic age of the similarly homogeneous belt of basic eruptive and irruptive rocks associated with the sediments of that formation. The purpose now, however, is not to insist upon the precise age of the stocks of peridotite and allied rocks of the ultra basic magnesian belt, but, rather, to point out that in spite of similarity of composition, structure, and age, they present strong contrasts in the degree or extent of serpentinization and hence, presumably, of the statenlithic development.

Recognizing that the process of serpentinization (and the same is true of chloritization) belongs, in the zone of katamorphism, not to the superficial and shallow belt of weathering, but to the deeper and vastly more extensive belt of cementation, we realize that climatic conditions must be eliminated as possible factors in the differentiation of the stocks. Hence the fact that in the northern half of the ultra-basic magnesian belt serpentinization is, superficially at least, more general, and, as a rule, more complete than in the southern half, is without climatic significance. The meaning of this contrast, which is to a large degree regional, is not readily apparent. But, whatever the initial cause of serpentinization, even though we tacitly assume its beginning, in any case, as essentially fortuitous or accidental, once begun this becomes a determining cause of its continuance; and the change spreads through the mass as a veritable mineral contagion.

Of more special interest now, however, is the fact that in Western North Carolina and elsewhere stocks of peridotite and of other rocks susceptible of the serpentine alteration are unaltered at least near the surface. This suggests that when the serpentinization of these masses begins, if not already begun, in the deep zone of cementation, the resultant statenlith must be, for a time, crowned with the unaltered peridotite or other original rock. We should, therefore, be prepared to recognize serpentine statenliths where no serpentine is exposed to observation. The relief of certain stocks of peridotite in Western North Carolina has been attributed to the supposed superior resistance to erosion of the peridotite as compared with the inclosing gneiss; but it is here suggested that deep-seated serpentinization, attested by peripheral slickensides, is an explanation worthy of some consideration.